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# *THE PHYSIOLOGICAL BASIS OF ILLUMINATION.*

By Louis Bell.

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# THE PHYSIOLOGICAL BASIS OF ILLUMINATION.

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THE purpose of this paper is to point out that with the existing knowledge of physiological optics artificial illumination can be removed from the domain of empiricism and can be made to rest upon constants which have a definite physiological basis and which can be and have been predetermined with reasonable precision. For obvious reasons data which relate to the sensation of sight cannot rank with exact physical measurements, but they can nevertheless be evaluated closely enough to give a reliable basis of judgment in planning illumination to meet any given requirements.

Except for the aid received from accommodation and in binocular vision from convergence, we see things in virtue of their differences of color and of luminosity. Of these two the latter is by far the more important, particularly in distant vision. Objects of similar luminosity but differing considerably in color blend into the general view in a most astonishing fashion when at any considerable distance. Objects of similar color but of different luminosity also fuse into the general field, and if color and luminosity are both similar, things disappear in a way that is positively amazing. Small colored areas of moderate luminosity blend even at relatively short range, — a fact which the impressionists have turned to extremely good use, albeit they often transfer to canvas the color vagaries of the tired eye and the effects of simultaneous contrast rather than the fleeting impressions which they hold so precious. One of Monet's landscapes, however, is wonderfully interesting from the standpoint of physiological optics, and especially in the existence of a critical distance, within which the picture loses its magic.

Practically, therefore, vision depends very largely upon the power of distinguishing differences of luminosity. And since objects in general are luminous only in virtue of light reflected from them, their visibility depends in turn upon their coefficients of reflection. So far at least as problems of artificial illumination are concerned, objects seen do not

range over a long scale of values of luminosity. Whatever the absolute values of the light reflected, the relative values expressed by the coefficients of reflection range from about 0.80 to about .01, very few substances returning more than the former or less than the latter percentage of the incident light.

The fundamental fact at the basis of vision is that the eye can perceive, within a very wide range of absolute intensity, a substantially constant fractional difference of luminosity. This is the purport of Fechner's law, and the fractional difference mentioned is well known as Fechner's fraction. Its numerical value for normal eyes and ordinary intensities of illumination is from .02 to .0055. The importance of this law in practical seeing is enormous, for in a room well lighted by diffuse daylight the illumination may vary from 100 meter-candles down to 10 or 20 in different parts of the room or at different times; and if power of discriminating difference of luminosity changed much with the illumination, one would be purblind most of the time. In some abnormal eyes Fechner's fraction, with vision otherwise normal, is considerably increased, with serious results. A case is cited by Krenchel in which a patient was unable to get about in full daylight without stumbling over things. His condition was most puzzling until a test showed Fechner's fraction at a value of 0.1. At this value one could not distinguish between dark and light shades of brown and gray, having coefficients of diffuse reflection of say .15 and .25 respectively, and ordinary shadows on neutral surfaces would therefore disappear entirely. With Fechner's fraction at 0.5 no contrast less than that between white and very dark pigments would be easily distinguished.

Now while Fechner's fraction is fairly constant over a wide range of intensities, one easily realizes that as twilight deepens his power of discriminating shades is seriously impaired. It is this variation of Fechner's fraction with the illumination which determines the minimum amount of artificial (or natural) light which is effective in enabling one to see things *en masse* in their natural relations. For general vision any illumination above that required to bring Fechner's fraction for the normal eye up to its steady value is needless, and, as we shall presently see, may be injurious.

Human vision, however, is frequently concerned with the observation of fine details both far and near, and the power of seeing these is within wide limits independent of the capacity of the eye for distinguishing small differences of luminosity. In the case mentioned by Krenchel this *visual acuity* was normal in spite of the extraordinary lack of sensitiveness to variations of light and shade. Acuity seems to depend on the structure of the retina and the quality of the eye as an optical in-

strument rather than on the direct or secondary sensitiveness of the nerve endings to stimulation by light. Great acuity is possibly commoner among savage peoples than in civilized races. König [1] has noted it among the Zulus, whose color vision, by the way, was normal; it has been found in unusual degree among the Kalmucks, and Johnson [2] noted it in the Congo peoples, in every case associated with slight hypermetropia. Some observations of Johnson (loc. cit.) would suggest that the extremely dark hue of the *fundus oculi* and consequent diminution of choroidal reflection found among the dark-skinned races may improve the definition, although perhaps at the expense of sensitiveness. It is of course well known that in the last resort the ability to separate objects like neighboring points and lines depends on the minute structure of the retina, and is greatest in the *fovea centralis*, where the cones are most closely packed. The fovea too is well known to be somewhat less light sensitive than the retina in general. Using a wedge photometer, I find for my own eye that there is a difference somewhat exceeding one stellar magnitude between the foveal visibility and that outside.

Following out this line of investigation, it is not difficult to project the fovea as a dull spot in the field of view. Using a wedge photometer and fixing the eye at any point on a large sheet of white paper, one finds, on rather quickly cutting down the light by sliding the wedge, a roundish dark spot exactly in the axis and corresponding in diameter with the projection of the fovea. It is not easy to hold vision of this phenomenon since the axis of the eye inevitably tends to wander.

By drawing five rather faint crosses at the centre and corners of a square, say a decimeter on a side, one can, by careful manipulation of the wedge, make the central cross disappear in the foveal blind spot while the corner crosses remain visible. The facts regarding the independence of acuity and sensitiveness lend weight to the theory of our confrère Professor Lowell regarding the bearing of this matter on astronomical observations. Extreme acuity and extreme sensitiveness being both rather rare, any considerable degree of independence must render the coexistence of both in the same individual unusual in a very much higher degree.

The failure of acuity in a dim light is familiar, and its variation with intensity affords an independent criterion of the necessary requirements in artificial illumination. Enough light must be provided to bring the eye to its normal acuity as well as to its normal value of Fechner's fraction. Fortunately the researches of Dr. Uhthoff [3] and of Drs.

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[1] Nature, **31**, 476.
[2] Phil. Trans., **194**, B. 61.
[3] Graefe's Arch., **32**, 171; **36**, 33.

König and Brodhun[4] on acuity and Fechner's fraction respectively give us safe ground on which to travel in these respects.

In Figure 1 are shown the acuity curves and the shade-perception curves of the normal eye for intensities up to 100 meter-candles. Curves *a* and *b* give the values of Fechner's fraction for white light and deep crimson light ($\lambda = 670\ \mu\mu$) respectively, while *c* and *d* give the acuity curves for light orange ($\lambda = 605\ \mu\mu$) and yellowish green ($\lambda = 575\mu\mu$) respectively. The ordinates in the first case are $\frac{dI}{I}$, and in the latter case are in arbitrary units. The most important feature of these curves for the purpose in hand is that they are already becoming asymptotic at low values of the illumination, and except for strong colors at about

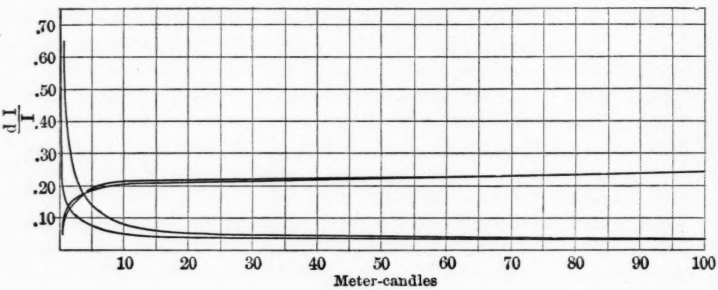


FIGURE 1.

the same point. At about 10 meter-candles they have turned well toward the axis, and beyond 20 meter-candles the gain in shade-perception and acuity is very slow with further increase. Hence, when the light reaching the eye has risen to 10 to 20 meter-candles, further increase does very little in the way of assisting practical vision.

Artificial illumination can be safely based on this amount as a working intensity. Visual acuity is the controlling factor in most indoor lighting. It varies noticeably with color, but for practical reasons, which will appear later, the actual visibility of colored objects depends not on the differences here shown so much as upon their general light-reflecting power, which for dark hues is always low.

At great intensities both shade-perception and visual acuity considerably decrease, the former at roughly 25,000 to 50,000 meter-candles, the latter at much lower intensity. Neither function is likely to fail at any

[4] Sitz. Akad., Berlin, 1888.

intensity reached in the ordinary course of artificial lighting, though acuity may be seriously interfered with by dazzling and consequent rapid retinal exhaustion at intensities of a few hundred meter-candles, and the same secondary cause also impairs shade-perception long before its final decline.

It must be clearly understood that in specifying 10 or 20 meter-candles as the intensity physiologically necessary to bring the eye into its normal working condition, these intensities are those which become visible to the eye, and not merely those that reach the objects under observation.

The light reflected from any object is $Ik$ where $I$ is the incident illumination and $k$ the coefficient of reflection. Then, if $a$ is the normal illumination just indicated, the required incident illumination is

$$I = \frac{a}{k}.$$

Taking, for example, $a = 15$ meter-candles, and assuming that one is observing white or very light colored backgrounds for which $k$ would have a mean value in the vicinity of 0.6, the value of $I$ should be about 25 meter-candles. If the background is dark fabric for which $k$ would not exceed 0.2, $I$ would rise to 75 meter-candles, and for black fabrics one could hardly get too much light. A typical application of the principle may be taken in a draughting room where tracing has to be done, and the drawing must be well seen through the tracing cloth. $k$ for tracing cloth is about .35, and the illumination which makes the drawing visible is reflected from the drawing paper behind and passed back through the tracing cloth. The drawing paper probably reflects, if slightly off white, as is common, about 60 per cent of the incident light, and the final coefficient of the combination falls to about 0.25. Taking the same value of $a$ as before, $I = 60$ meter-candles. Ordinary draughting rooms are found to be well lighted at this intensity. It should be noted that draughtsmen generally use hard pencils, which make marks contrasting rather weakly with the paper, so that strong illumination is needed at all times.

In illumination out of doors, as upon the street, where no weak contrasts or fine details need to be made out, $a$ may be taken very much lower, but $k$ is also low, and the minimum of about .25 or .30 meter-candle often allowed between lamps is, as the curves show, considerably too small for good seeing.

*Effect of Pupillary Aperture.* The iris serves as an automatic stop behind the cornea, adjusting itself so as to protect the retina from too violent changes of brilliancy. It may vary in diameter of aperture

from less than 1 mm. up to the full diameter of the visible iris, which in the darkness may retreat even within the rim of the cornea, as Du Bois-Reymond[5] has shown. The eye therefore works over an aperture range varying from *f*20 or more down to *f*2.5 or *f*2. Incidentally the iris, acting as a stop behind the strongly refracting cornea, produces a certain amount of typical "pincushion distortion" which is evident in some optical illusions.

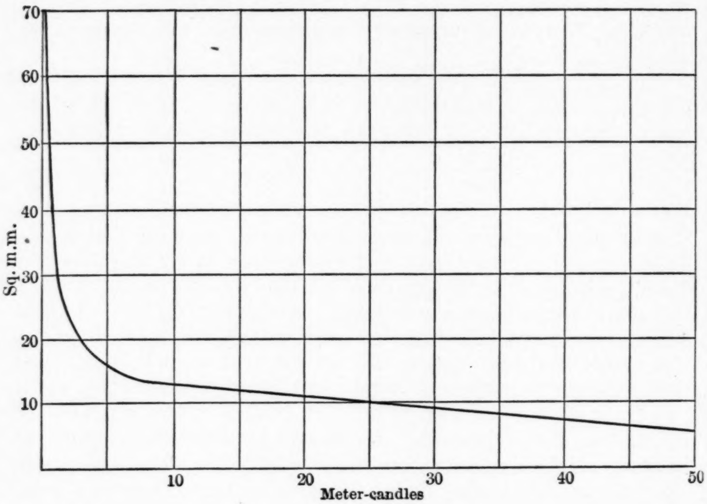


FIGURE 2.

Data on the actual relation between intensity of incident light and pupillary aperture are scarce and imperfect. So much depends on the state of adaptation of the eye, individual sensitiveness, and probably also upon the intrinsic brightness of the source, that reliable values of the relation are difficult to obtain. From a reduction of Lambert's data, however, I have plotted the curve of Figure 2, giving as abscissae the illumination in meter-candles and as ordinates the area of the pupil in square millimeters. The striking fact is at once in evidence that this curve, like those of Figure 1, is rapidly becoming asymptotic in the neighborhood of 10 meter-candles. In other words, the contraction and expansion of the iris is less to protect the eye at high intensities

[5] Centralbl. f. prakt. Augenheilkunde, 1888.

than to strengthen the retinal image at low intensities, even at the expense of considerably impaired definition. The human eye seems, however, to have become specialized for considerable acuity in a moderate light rather than for such extreme sensitiveness as is found in many nocturnal animals whose pupillary apertures vary over a much wider range than in man.

The curves of Figure 1 show simple retinal sensitiveness, and in reckoning from them one must at low illuminations take account of the gain from increased aperture. At ordinary working values of the illumination the gain is small, but at 1 or 2 meter-candles it is very material and plays a most important part in practical vision. For example, by curve *a*, Figure 1, an illumination of 0.5 meter-candle would imply a value of Fechner's fraction of about 0.2, which would in turn imply very much impaired shade-perception. In point of fact, one can see quite tolerably by a candle at the equivalent distance of 1.4 meters.

For if the pupil has adjusted itself to this situation the virtual illumination is that corresponding to about 2 meter-candles, the equivalent area of the pupil having increased to at least four times its ordinary value, which is that to which the curves of Figure 1 pertain. The result is a value of 0.1 or less for Fechner's fraction, which is quite another matter.

Were it not for this assistance, it would be quite impossible to get accurate photometric readings at the low intensities common upon the photometer screen. Similarly it would be exceeding difficult to get about at night, even by moonlight. In this latitude moonlight near full moon may fall to about 0.2 meter-candle, which would give Fechner's fraction at nearly .5, barring aid from the iris. With this aid increasing the aperture perhaps 6 times, one can see to get about very easily and can even read very large print. The same conditions have an important bearing on vision in presence of a strong radiant. For example, suppose that in a general illumination of 1 meter-candle one can make out objects having a contrast $\frac{dI}{I} = .15$. Then let a light giving 20 meter-candles come fairly into the field of vision without materially illuminating these objects. The pupil will close to about one third its former area, giving a virtual illumination of about 0.3 meter-candles and a shade-perception of about .30, in which, of course, the objects disappear. Hence one cannot see well across a bright light, and even objects illuminated by it lose in visibility unless the change in illumination from them is greater than the concomitant change in aperture ratio.

The loss in visibility by the presence of a brilliant radiant in the field of view is increased by the change in adaptation of the eye. It is also probable that the intrinsic brilliancy of the radiant, as well as the light received from it, has a bearing on the pupillary aperture. Certainly at equal illuminations a well-shaded lamp gives higher visibility than a bare one, both being assumed to be in the field of view. There is therefore every reason for keeping such things as bare gas lights and electric lamps entirely out of the visual field, only admitting them thereto when they are so shaded as to keep the intrinsic brilliancy to low limits.

The eye has been evolved under conditions that imply rather moderate intrinsic brilliancy, admitting the general desire to keep the direct rays of the sun out of one's eyes. Sky light, of course, varies very widely in apparent intensity, being most intense in the presence of white cloud of moderate density. An average all the year round mean for the northern part of the United States, giving the intrinsic brilliancy of an aperture fully exposed to the upper sky, would be from measurements by Dr. Basquin,[6] in the neighborhood of 0.4 candle power per square centimeter. This is lower than the intrinsic brilliancy of any flame, and approximates that of a bright lamp behind a thin opal shade. The ordinary window, which is in a wall rather than the roof, and gets its light largely from low altitudes and somewhat reduced by trees or buildings, is much less brilliant.

For instance, a window 1 m. wide and 2 m. high would be unusually effective if it gave 50 meter-candles at a point 5 m. within the room. This illumination would imply a virtual intensity of about 1250 candles at the window or an intrinsic brilliancy over the window area of 0.0625 candle power per square centimeter. Natural intrinsic brilliancies are decidedly low, and the chief difference between natural and artificial illumination, from the standpoint of wear and tear upon the visual organs, is the high intrinsic brilliancy of artificial light. If radiants are to be within the field of vision, they should be screened by diffusing globes or shades down to a maximum intrinsic brilliancy of preferably not above 0.1 or 0.2 candle power per square centimeter, certainly not above double these figures. As I have pointed out in a former paper,[7] if one plots the pupillary apertures as ordinates and the function $\frac{1}{\sqrt{I}}$ as abscissae, the result is nearly a straight line, so that if one measures the visual usefulness $u$ of a certain illumination

[6] The Illuminating Engineer, Jan., 1907.
[7] Trans. Ill. Eng. Soc., July, 1906.

$I$ in terms of what one may call the *admittance* of the pupil, then approximately

$$u = c\sqrt{I},$$

assuming that $I$ is within ordinary ranges of intensity; that is, the eye works most efficiently at moderate illumination. The adverse factors in lowering the illumination are the optical errors introduced by increase of pupillary aperture and the general failure of shade-perception and acuity as the illumination falls below about 10 meter-candles. Spherical aberration and astigmatism increase rapidly at large apertures, so that definition of objects is much impaired. This doubtless plays its part in the failure of acuity in very poor light, although a more prominent fact is the increase of acuity as the eye is stopped down at illuminations considerably above the critical value at which the eye comes into normal working condition.

This critical value to which shade-perception, acuity, and pupillary reaction all point relates, it must be remembered, to the illumination received from the objects viewed considered as secondary light-sources. In too strong light thus received the eye is as seriously dazzled as if the source were a primary one, and the usual effects of after images and other evidences of retinal exhaustion and irritation at once appear. In very insufficient illumination there is failure to see contrast and detail, and there is an instinctive effort to push the eye near to the object at the risk of straining the mechanism of accommodation seriously. The familiar success of this expedient opens up some of the most curious questions of physiological optics.

Suppose, for instance, that one is viewing white letters on a dark ground. Evidently the letter acts as a secondary source of illumination, which proceeds from it, following the law of inverse squares. Now by halving the distance to the eye the intensity at the pupil is quadrupled, and at first thought one would infer that inspection of the shade-perception and acuity curves would give ample reason for the gain in visibility. But at half the distance the object subtends double the visual angle, and the retinal image is therefore quadrupled in area, leaving the luminous energy per unit of area the same as before; why, therefore, any gain in visibility? A similar question in a more aggravated form arises in accounting for improved vision through night glasses.

The key to the situation is found in the fact, put on a sound experimental basis by Dr. Charpentier,[8] that for the visible brightness of

[8] "La Lumière et les couleurs," p. 138 et seq.

objects giving images less than about 0.15 mm. in diameter the simple law of inverse squares holds. In other words, for weak stimuli at least, the visibility of small objects is determined by the total light emitted and by the distance and not by the surface brilliancy. It is as if a retinal area of about 0.15 mm. diameter acted as a visual unit, all stimuli acting upon this as a whole. As Charpentier (loc. cit.) puts the case with reference to distance, "In a word, the apparent brightness of a luminous object varies, other things being equal and within the limits indicated, in inverse ratio with the square of its distance from the eye."

As the eye then approaches a luminous object its apparent brightness increases, and it is distinguished more plainly so long as its image dimension is anywhere within the limit mentioned. As this corresponds to an object 2 mm. long at a distance of about 20 cm., the rule holds for reading type and the observation of small objects generally. The cause of this phenomenon is somewhat obscure. The natural supposition that it might well be due to spherical aberration and faulty accommodation in an eye with its pupil expanded, fails, as Charpentier (loc. cit.) shows, in two ways. First, the circle of diffusion in the eye due to spherical aberration is much smaller than the critical diameter in this case, and second, the phenomenon occurs when the eye is stopped by a diaphragm. I have tried it with a wedge photometer provided with a pair of 2 mm. apertures in line and separated by 6 mm., so that the ray pencil was of very narrow aperture, and find it still very conspicuous and apparently unchanged.

Charpentier and others are disposed to think its origin purely retinal, resulting from the spreading of the stimulus over retinal elements adjacent to those immediately concerned, and closely allied to the phenomenon of irradiation.

This latter phenomenon, however, is charged by Helmholtz largely to aberrations and dioptric faults generally. One of the best sources for studying irradiation is an incandescent lamp filament. At a distance of say 2 meters the apparent diameter of the filament at full incandescence is 4 or 5 mm. Using the wedge photometer upon it, the diminution of apparent diameter is at first rapid, until it falls to about 0.5 mm., at which it remains nearly constant until it completely vanishes. Stopping down the pencil of rays to 1 mm. or so cuts off most of the irradiation, but this seems to act in the main merely as a reduction of intensity, since the same effect is produced by a similar reduction in intensity by the wedge retaining the full aperture of about 5 mm. At a few hundredths of a meter-candle most of the irradiation has disappeared. The apparent breadth of the filament decreases without any

marked shading off at the edges, something as if a slit were being closed. The appearances indicate that beside the undoubted aberrations which come into play, there is considerable spreading of light in the retina at high intensities, reinforced very likely by reflection from the choroid, producing an effect quite analogous to the halation observed in a photographic plate.

The dimensions of the irradiation effect thus observed are inferior to the dimensions required by Charpentier, but it is quite probable that with a dark-adapted eye and feeble illumination, lessened contrast with the chief image would render the outlying portions more conspicuous.

The increased visibility of rather large areas is a still more puzzling matter, for which no satisfactory explanation has been produced. Inasmuch as all dealings like these with threshold sensibility have by this condition eliminated the cones of the retina from action, and depend upon rod vision entirely, it may be, since the rods are relatively more numerous away from the fovea, that mere size of image insures its falling on retinal areas relatively rich in active visual elements.

Aside from questions of intensity in artificial illumination is the matter of steadiness. It is of course well known that violent transitions of light and darkness, whether by moving the person or the eye, or by changing the intensity of the light itself, are distressing and injurious. The retina has a certain amount of visual inertia, which furnishes protection against very rapid changes, else one could not use lights successfully with alternating current. Flicker, from a practical standpoint, is troublesome about in direct proportion to its magnitude and in inverse proportion to its frequency. A change of intensity, however, covering some seconds, giving the iris plenty of time for readjustment, is hardly noticeable, while one of the same numerical magnitude, say 20 per cent each side of the mean, occurring once or a few times per second, is most painful. Ordinary incandescent lamps run on alternating current vary from 5 to 15 per cent on each side of the mean, according to the thermal inertia of the filament, and the frequency. With lamps of ordinary voltage and candle power the flickering is perceptible at between 20 and 30 cycles per second, the new high-efficiency lamps being worse than the older ones. Practically all lighting is done at above 30 $\sim$, and troublesome flickering comes only from the irregular fluctuations of bad service. It must not be forgotten that one can impress serious fluctuations of light on the retina by compelling the eye to confront great variations of illumination when it moves. No artificial light should be arranged so that it forces the eye to make sudden transitions from blackness to brilliancy. Figure 3 is given here as a horrible example of what should never be permitted. I am sorry

to say that it is from the catalogue of a maker of reflectors who should have known better. Note the blackness of the interior and the excessive brilliancy of the light on the work.

In this connection should be mentioned the trouble that may come from the glare of light reflected from white paper, a risk to which bookkeepers are especially subject. I have been in counting rooms where I found every clerk with signs of bad eyes.

Much paper is too highly calendered, and from this cause gives a combination of regular and diffuse reflection. Obviously a mirror placed on one's desk would give at certain angles an image of the lamp

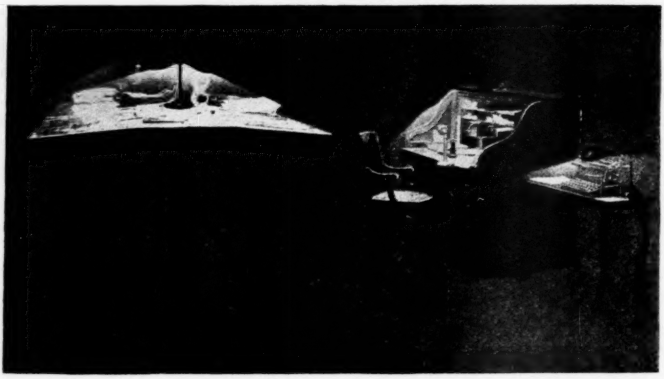

FIGURE 3.

of distressing brilliancy, and as the head might move this image would dodge into and out of the field of vision, giving an added cause of trouble. Glossy paper does somewhat the same thing. Figure 4 shows from Trotter's data[9] the relative reflection at various angles of incidence from ordinary Bristol board (*a*) and from the nearly pure matte surface of freshly set plaster of Paris (*b*). The sharp peak corresponding to the angle of regular reflection is very striking. Light on a desk should therefore come from the side or rear rather than from the front, especially if the source is of high intrinsic brilliancy. For a similar reason the direction of illumination should be such as to free the eye from the effect of wavering shadows of the hand or head. The avoidance of shadow from the hand is the rationale of the sound old rule

[9] The Illuminating Engineer, **1**, 488.

that the light should come from the left (left-handed people were forgotten). Shadows from the head and shoulders are much more troublesome, as they may exist to an annoying degree in rooms other-

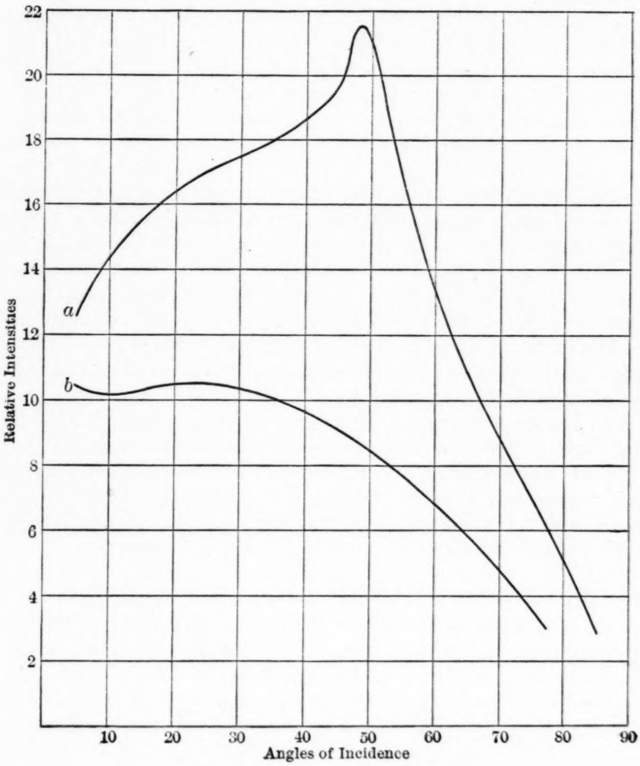


FIGURE 4.

wise well lighted, and they are in fact difficult to avoid in the general lighting of counting rooms and similar places.

Finally, one is nowadays often confronted by questions of color. Until electric lighting in its more recent forms appeared there was a sufficient similarity in the colors of artificial illuminants to place them substantially on a parity. At present, strong colors are common, and

are likely to be increasingly so, since, as I have noted in a previous paper (loc. cit.), selective radiation is necessary to high luminous efficiency. One has to deal with the yellow of the flaming arc, the yellowish green of the Welsbach, the blue green of the mercury tube, and the violet of the enclosed arc, all of which may have to be compared with the deep orange of the Hefner lamp.

Practically the question of suitable color resolves itself into two parts, — first, the effect of color on the proper functioning of the visual apparatus, and second, its relation to our observation of colored objects. I shall not take up here the theories of color vision, save to note that many of their difficulties may now be charged to the existence of at least two kinds of independent visual elements, the rods and cones, differently distributed in the retina, and possessing two radically different types of visual sensitiveness. That the cones are highly evolved rods has been shown beyond much doubt by Cajal, and is in evidence in the simple rod structure found in the parietal eyes of some fishes and lizards and in lower organisms generally. Whether, as Mrs. Franklin [10] surmised, there are definite intermediate phases of sensitiveness between the achromatic vision of the rods and the full chromatic vision of the cones is an important topic for research.

May I venture to suggest that there are some reasons for thinking that there may even be a difference in kind between a simple photochemical rod stimulation and the strongly selective stimulation of the highly specialized cones? Selective activity does not necessarily connote chemical instability. They may coexist, as in some organic dyestuffs, or may be entirely independent, as in the fluorescence of heavy paraffin oils. The presence of strong pigmentation at the rods and its absence at the cones, coupled with the absence of visual purple in some nocturnal creatures whose eyes are presumably specialized for very weak light, suggests that the evolution of the retinal elements may have proceeded along more than one line. In fact, the Young-Helmholtz and Hering doctrines may find in a heterogeneous retina a certain amount of common ground. Be this as it may, mankind certainly has superimposed a very sensitive but achromatic rod vision, and a much less sensitive but chromatic cone vision, the latter being mainly central and the former mainly peripheral. The passage from predominant rod vision to predominant cone vision is shown in the sharp flexure of the curves in Figure 1. The exact point at which the color sensitive cones begin to get into action undoubtedly varies greatly in different eyes, and in the same eye in different conditions of adaptation. As the

[10] Mind, N. S., **2**, 473 et seq.

illumination is progressively diminished, color vision gets more and more imperfect and uncertain, especially toward the red end of the spectrum. The effect is shown very clearly in the variation of Fechner's fraction with color as the intensity changes. Figure 5 shows the change in $\frac{\partial I}{I}$ with $\lambda$ for intensities of 15 meter-candles ($a$) and 0.75 meter-candles ($b$) respectively from the data obtained by König and Brodhun (loc.

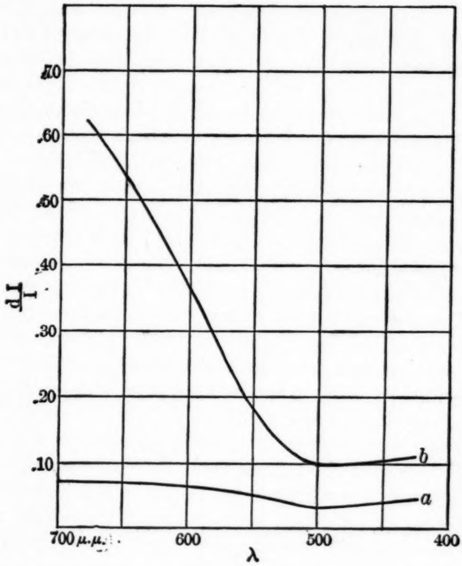


FIGURE 5

cit.). Looking at the latter, it is evident that for the orange and red, vision must be very poor indeed, and in no part of the spectrum really good. In curve $a$ color vision is pretty well established, although there are still traces of the point of inflection, which, as we shall presently see, falls near the point of maximum sensitiveness in very weak light, as if the superimposed rod vision were still helping out at this moderate intensity.

The Purkinje phenomenon, now well known to depend on the progressive failure of cone vision, also gives valuable evidence along the same line. It was noticed more than twenty years ago by Professor

Stokes[11] that the phenomenon varied with the areas involved, and recently Dow[12] has found that for small areas (*i. e.*, nearly central and hence mainly pure cone vision) Purkinje's phenomenon appears only below about 0.2 meter-candle. This figure would quite certainly have been somewhat higher had he used instead of red and signal-green glass the primary red and green, but it is clear from his results that the superposition of rod vision has a very considerable effect at moderate illuminations.

Finally, one must consider the luminosity curves at various intensities. Figure 6 gives in curve *a* the relative luminosities of the spectrum colors at fairly high intensity. The maximum is in the yellow, and the falling off, especially on the red side, is very rapid. This seems to be about the normal curve when the eye is fully in action. Curve *b* gives the luminosity curve for an intensity of about 0.0007 meter-candle. At this point color sensation is practically extinguished, and the maximum luminosity is perceptible, in what would seem the pure green were the light brighter, very near the E line and at a point corresponding to the inflection in the curves of Figure 5. This is practically the condition of pure rod vision. Curve *c*, Figure 6, lends confirmatory evidence. It is the luminosity curve obtained by Abney[13] from a patient with pure monochromatic vision. He had apparently an absolute central scotoma (cones atrophied rather than replaced by rods?), visual acuity greatly subnormal (central vision absent), and nyctalopia. This is a typical condition, nyctalopia being generally associated with central color scotoma, leaving peripheral vision but slightly affected (Fick). The patient apparently had no color perception, and his luminosity curve was practically identical with *b*, the normal curve for very weak light.

It would be most interesting to get proper tests for luminosity in one of the rare cases of congenital hemeralopia which would present the reverse condition of rods inactive and cones nearly normal. A comparison of such a case with luminosity in the hemeralopia associated with *retinitis pigmentosa*, in which peripheral vision is progressively contracted, might give valuable evidence as to the existence of retinal elements intermediate in function between rods and cones.

To sum up this phase of the matter, rod vision seems to be predominant from the very threshold illumination up to several tenths of a meter-candle, and to continue in force to all ordinary intensities, although rather easily exhausted. It gives low visual acuity and shade-perception perhaps of the order of a tenth normal, but, such as it is, it is our

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11 Nature, **32**, 537.

12 Phil. Mag., Aug., 1906.

13 Proc. Roy. Soc., **66**, 179.

main nocturnal reliance. Cone vision begins to come perceptibly into play at a few thousandths of a meter-candle, and at a few tenths is

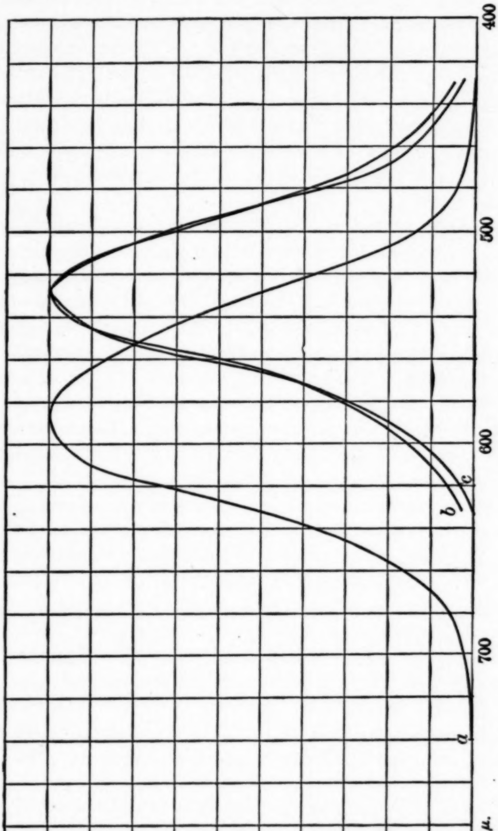


FIGURE 6.

pretty well established, but does not become normal over the visual area below five or ten meter-candles, and gains materially even beyond that, especially in acuity, which is weak at the lower intensities.

Acuity in practical degree is chiefly an attribute of cone vision. The general theory of optical resolution requires acuity inversely as the wave-length of the light concerned. In practice this difference is in great measure masked by other and larger causes of variation. Chief among these is the very low luminosity of the shorter wave-lengths on the one hand and of the very long ones on the other. For example, in comparing acuity at $\lambda = 500\ \mu\mu$ and $\lambda = 650\ \mu\mu$ there is a proportional difference really due to color, but a ratio of 2.5 : 1 in luminosity in further favor of the green. Violet light favors acuity, if one can get enough of it, but a luminosity of .02 of the maximum in the yellow stands in the way.

Certain strongly colored lights, like the flaming calcium fluoride arc and the mercury arc, give apparently extremely sharp definition in black and white objects. In general this is not due to any advantage in color as such, but to improvement in the conditions of chromatic aberration in the eye. At rest for distant vision, the normal eye is in focus for the rays of maximum luminosity, and the focus for blue lies perhaps 0.4 mm. in front of the retina. That is, the eye is short-sighted for short rays. In near vision the rear conjugate focus moves backwards and the eye finds focus on the blue with less accommodation than usual. Thus Dow [14] finds that, while the mercury arc gives easy and sharp definition for near vision, at a distance of twenty feet or even less it becomes difficult to get focus. Lord Rayleigh [15] noticed some years ago that in very weak light he became myopic and required a glass of —1 diopter to restore normal vision. This effect is of the order of magnitude required by the shift of maximum luminosity into the green at very low intensities. Another phase of chromatic aberration is even more important. Were it not for the existence of a very high maximum in the luminosity curve, distinct vision would be impossible, since the difference of focus between the red and violet in the eye is something like 0.6 mm.; and were these extreme colors highly luminous, there would be no focal surface to which the eye could adjust itself. Only the great predominance of the central colors in luminosity gives the chance for a fairly sharp image.

It is easy to show the difficulties into which equal luminosity throughout the spectrum would plunge us. If one forms a grid of certain purples by cutting strips of tissue paper of the required color perhaps 5 mm. wide and 100 mm. long and pasting them upon a dark neutral background spaced about their width apart, one readily finds

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[14] The Illuminating Engineer, **2**, 26 et seq.
[15] Nature, **31**, 340.

the practical effect of chromatic aberration. From a distance of a couple of meters sharp definition of the grid is quite impossible. The purple chosen should give considerable absorption of the green, yellow, and orange, leaving strong red and blue evenly balanced in luminosity, and the background should be of not greatly different luminosity, so that the eye must rely mainly upon color effects. The rays from the grid are then of two widely different colors, for which the focal length of the eye differs. There are therefore two image surfaces of about equal intensity perhaps half a millimeter apart, and the effect is a curious blur, the eye hunting in vain for something definite upon which to focus.

Interposing now a deep red screen (concentrated saffronine is good), or a suitable blue screen, the image of the grid becomes nearly monochromatic and appears sharply defined. This is an extreme case, but any monochromatic light has an advantage in definition if other conditions are at all favorable. It seems highly probable that the well-known trouble found at twilight in trying to work by a mixture of natural and artificial light is due to a similar cause. The predominant hue of diffused sky light is strongly blue, while that of gas flames, incandescent lamps, and like sources, is strongly yellowish. At a certain point in the fading of daylight the luminosities of these widely different colors should balance closely enough to produce something of the effect just described, although the usual difference of direction in the two superimposed illuminations may play a part in the general unpleasant effect.

There is, however, an inherent danger in using monochromatic or strongly colored light for general purposes. Whatever may be the nature of color vision, a strongly colored light utilizes only a part of the visual apparatus. If of high intensity to make up for inherently low luminosity, it rapidly exhausts that part, and produces, as is well known, a temporary color blindness. There is at least a serious chance that long continued use of colored light would produce persistent and perhaps permanent damage to color perception. A light nearly white, with its maximum luminosity near the normal wave-length, runs the least chance of imposing abnormal strains on the visual apparatus.

In color discrimination the same rule holds good, for any considerable departure from white leads to entirely false color-values. In closing I may mention an interesting question which arises with reference to obtaining a light of high efficiency by building it up from the monochromatic primary components. Would the eye see clearly by such a light, and could it discriminate colors properly? The answer is probably yes. The equation for white is roughly

$$W = .20\,R + .30\,G + .50\,B.$$

These are quantities as determined by slit width in the spectrum or a like process. There is sufficient predominance of luminosity in the green to avoid trouble from chromatic aberration, and the actual working of the combination in giving photographs in natural colors is such as to indicate proper color vision. As yet, however, no means are available for producing all three primary colors efficiently, and for white artificial light we are compelled to rely on what is in effect building up a nearly continuous spectrum from heterogeneous components, unless as usual we employ the continuous spectrum of an incandescent solid.